Processing the Shuttle for Flight

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Preparing the Shuttle for Flight

Ground Processing

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When taking a road trip, it is important to plan ahead by making sure your vehicle is prepared for the journey. A typical road trip on Earth can be routine and simple. The roadways are already properly paved, service stations are available if vehicle repairs are needed, and food, lodging, and stores for other supplies can also be found. The same, however, could not be said for a Space Shuttle trip into space. The difficulties associated with space travel are complex compared with those we face when traveling here. Food, lodging, supplies, and repair equipment must be provided for within the space vehicle.

Vehicle preparation required a large amount of effort to restore the shuttle to nearly new condition each time it flew. Since it was a reusable vehicle with high technical performance requirements, processing involved a tremendous amount of "hands-on" labor; no simple tune-up here. Not only was the shuttle's exterior checked and repaired for its next flight, all components and systems within the vehicle were individually inspected and verified to be functioning correctly. This much detail work was necessary because a successful flight was dependent on proper vehicle assembly. During a launch attempt, decisions were made within milliseconds by equipment and systems that had to perform accurately the first time—there was no room for hesitation or error. It has been said that a million things have to go right for the launch, mission, and landing to be a success, but it can take only one thing to go wrong for them to become a failure.

In addition to technical problems that could plague missions, weather conditions also significantly affected launch or landing attempts. Unlike our car, which can continue its road trip in cloudy, windy, rainy, or cold weather conditions, shuttle launch and landing attempts were restricted to occur only during optimal weather conditions. As a result, weather conditions often caused launch delays or postponed landings.

Space Shuttle launches were a national effort. During the lengthy processing procedures for each launch, a dedicated workforce of support staff, technicians, inspectors, engineers, and managers from across the nation at multiple government centers had to pull together to ensure a safe flight. The whole NASA team performed in unison during shuttle processing, with pride and dedication to its work, to make certain the success of each mission.

Preparing the Shuttle for Flight

Ground Processing

Imagine embarking on a one-of-a-kind, once-in-a-lifetime trip. Everything must be exactly right. Every flight of the Space Shuttle was just that way. A successful mission hinged on ground operations planning and execution.

Ground operations was the term used to describe the work required to process the shuttle for each flight. It included landing-to-launch processing—called a "flow"—of the Orbiter, payloads, Solid Rocket Boosters (SRBs), and External Tank (ET). It also involved many important ground systems. Three missions could be processed at one time, all at various stages in the flow. Each stage had to meet critical milestones or throw the entire flow into a tailspin.

Each shuttle mission was unique. The planning process involved creating a detailed set of mission guidelines, writing reference materials and manuals, developing flight software, generating a flight plan, managing configuration control, and conducting simulation and testing. Engineers became masters at using existing technology, systems, and equipment in unique ways to meet the demands of the largest and most complex reusable space vehicle.

The end of a mission set in motion a 4- to 5-month process that included more than 750,000 work hours and literally millions of processing steps to prepare the shuttle for the next flight.

Landing

During each mission, NASA designated several landing sites—three in the Continental United States, three overseas contingency or transatlanic abort landing sites, and various emergency landing sites located in the shuttle's orbital flight path. All of these sites had one thing in common: the commander got one chance to make the runway. The Orbiter dropped like a rock and there were no second chances. If the target was missed, the result was disaster.

Kennedy Space Center (KSC) in Florida and Dryden Flight Research Center (DFRC)/Edwards Air Force Base in California were the primary landing sites for the entire Space Shuttle Program. White Sands Space Harbor in New Mexico was the primary shuttle pilot training site and a tertiary landing site in case of unacceptable weather conditions at the other locations.

The initial six operational missions were scheduled to land at DFRC/Edwards Air Force Base because of the safety margins available on the lakebed runways. Wet lakebed conditions diverted one of those landings—Space Transportation System (STS)-3 (1982)—to White Sands Space Harbor. STS-7 (1983) was the first mission scheduled to land at KSC, but it was diverted to Edwards Air Force Base runways due to unfavorable Florida weather. The 10th shuttle flight—STS-41B (1984)—was the first to land at KSC.

Landing Systems

Similar to a conventional airport, the KSC shuttle landing facility used visual and electronic landing aids both on the ground and in the Orbiter to help direct the landing. Unlike conventional aircraft, the Orbiter had to land perfectly the first time since it lacked propulsion and landed in a high-speed glide at 343 to 364 km/hr (213 to 226 mph).

Following shuttle landing, a convoy of some 25 specially designed vehicles or units and a team of about 150 trained personnel converged on the runway. The team conducted safety checks for explosive or toxic gases, assisted the crew in leaving the Orbiter, and prepared the Orbiter for towing to the Orbiter Processing Facility.

The landing-to-launch ground operations "flow" at Kennedy Space Center prepared each shuttle for its next flight. This 4- to 5-month process required thousands of work hours and millions of individual processing steps.

Space Shuttle Atlantis landing, STS-129 (2009).

After landing, the Orbiter is moved to the Orbiter Processing Facility.

Landing

Orbiter Processing Facility: 120-130 days

Orbiter Processing

The Orbiter Processing Facility was a sophisticated aircraft hangar (about 2,700 m² [29,000 ft²]) with three separate buildings or bays. Trained personnel completed more than 60% of the processing work during the approximately 125 days the vehicle spent in the facility.

Technicians drained residual fuels and removed remaining payload elements or support equipment. More than 115 multilevel, movable access platforms could be positioned to surround the Orbiter and provide interior and exterior access. Engineers performed extensive checkouts involving some 6 million parts. NASA removed and transferred some elements to other facilities for servicing. The Orbiter Processing Facility also contained shops to support Orbiter processing.

Tasks were divided into forward, midbody, and aft sections and required mechanical, electrical, and Thermal Protection System technicians, engineers, and inspectors as well as planners and schedulers. Daily activities included test and checkout schedule meetings that required coordination and prioritization among some 35 engineering systems and 32 support groups. Schedules ranged in detail from minutes to years.

Personnel removed the Orbital Maneuvering System pods and Forward Reaction Control System modules and modified or repaired and retested them in the Hypergolic Maintenance Facility. When workers completed modifications and repairs, they shipped the pods and modules back to the Orbiter Processing Facility for reinstallation.

Johnson Space Center Orbiter Laboratories

Several laboratories at Johnson Space Center supported Orbiter testing and modifications.

The Electrical Power Systems Laboratory was a state-of-the-art electrical compatibility facility that supported shuttle and International Space Station (ISS) testing. The shuttle breadboard, a high-fidelity replica of the shuttle electrical power distribution and control subsystem, was used early in the program for equipment development testing and later for ongoing payload and shuttle equipment upgrade testing. During missions, the breadboard replicated flow problems and worked out solutions.

Engineers also tested spacecraft communications systems at the Electronic Systems Test Laboratory, where multielement, crewed spacecraft communications systems were interfaced with relay satellites and ground elements for end-to-end testing in a controlled radio-frequency environment.

The Avionics Engineering Laboratory supported flight system hardware and software development and evaluation as well as informal engineering evaluation and formal configuration-controlled verification testing of non-flight and flight hardware and software. Its real-time environment consisted of a vehicle dynamics simulation for all phases of flight, including contingency aborts, and a full complement of Orbiter data processing system line replacement units.

The Shuttle Avionics Integration Laboratory was the only program test facility where avionics, other flight hardware (or simulations), software, procedures, and ground support equipment were brought together for integrated verification testing.

Inside the Orbiter Processing Facility, technicians process the Space Shuttle Main Engine and install it into the Orbiter.

Orbiter Processing Facility (continued)

Kennedy Space Center Shuttle Logistics Depot

Technicians at the Shuttle Logistics Depot in Florida manufactured, overhauled and repaired, and procured Orbiter line replacement units. The facility was certified to service more than 85% of the shuttle's approximately 4,000 replaceable parts.

At the Shuttle Logistics Depot, Rick Zeitler assesses the cycling of a main propulsion fill and drain valve after a valve anomoly during launch countdown caused a scrub.

This facility established capabilities for avionics and mechanical hardware ranging from wire harnesses and panels to radar and communications systems, and from ducts and tubing to complex actuators, valves, and regulators. Capability included all aspects of maintenance, repair, and overhaul activities.

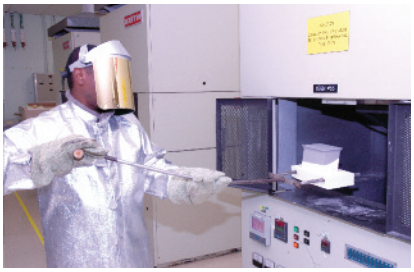
Kennedy Space Center Tile Processing

Following shuttle landing, the Thermal Protection System—about 24,000 silica tiles and about 8,000 thermal blankets—was visually inspected in the Orbiter Processing Facility.

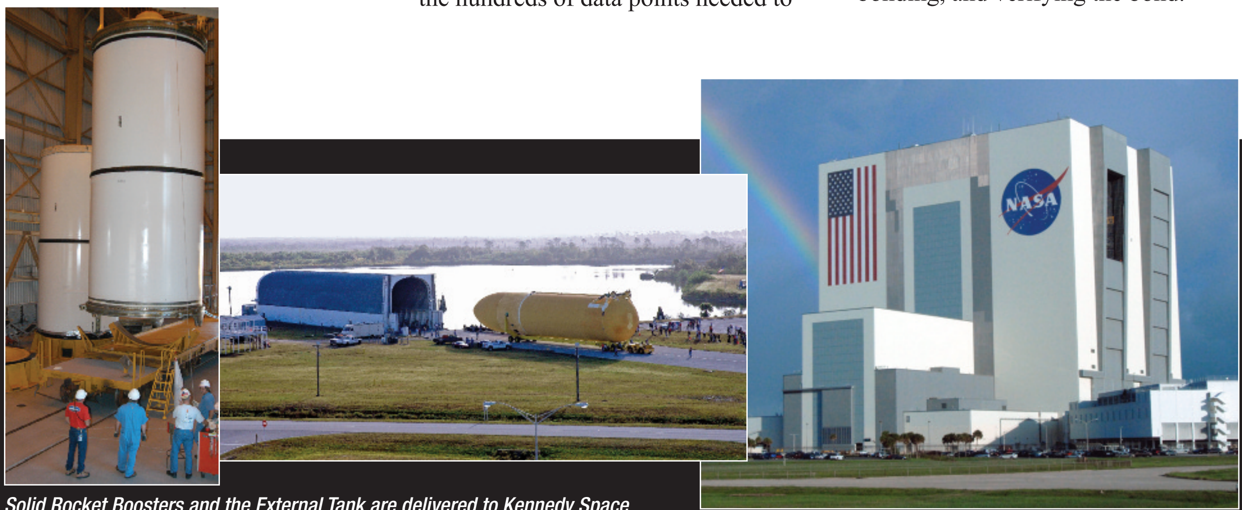
Thermal Protection System products included tiles, gap fillers, and insulation blankets to protect the Orbiter exterior from the searing heat of launch, re-entry into Earth's atmosphere, and the cold soak of space. The materials were repaired and manufactured in the Thermal Protection Systems Facility.

Tile technicians and engineers used manual and automated methods to fabricate patterns for areas of the Orbiter that needed new tiles. Engineers used the automotive industry tool Optigo™ to take measurements in tile cavities. Optigo™ used optics to record the hundreds of data points needed to manufacture tile accurate to 0.00254 cm (0.001 in.). Tile and external blanket repair and replacement processing included: removal of damaged tile and preparation of the cavity; machining, coating, and firing the replacement tile; and fit-checking, waterproofing, bonding, and verifying the bond.

Prior to the launch of STS-119 (2009), Discovery gets boundary layer transition tile, which monitors the heating effects of early re-entry at high Mach numbers.



At the Kennedy Space Center tile shop, a worker places a Boeing replacement insulation 18 tile in the oven to be baked at 1,200°C (2,200°F) to cure the ceramic coating.



Solid Rocket Boosters and the External Tank are delivered to Kennedy Space Center and transported to the Vehicle Assembly Building to be readied for the Space Shuttle.

Vehicle Assembly Building: 7-9 days

Space Shuttle Main Engine Processing

Trained personnel removed the three reusable, high-performance, liquid-fueled main engines from the Orbiter following each flight for inspection. They also checked engine systems and performed maintenance. Each engine had 50,000 parts, about 7,000 of which were life limited and periodically replaced.

Solid Rocket Booster Processing

The SRBs were repaired, refurbished, and reused for future missions. The twin boosters were the largest ever built and the first designed for refurbishment and reuse. They provided “lift” for the Orbiter to a distance of about 45 km (28 miles) into the atmosphere.

Booster Refurbishment

Following shuttle launch, NASA recovered the spent SRBs from the Atlantic Ocean, disassembled them, and transported them from Florida to ATK’s Utah facilities via specially designed rail cars—a trip that took about 3 weeks.

After refurbishment, the motor cases were prepared for casting. Each motor consisted of nine cylinders, an aft dome, and a forward dome. These elements were joined into four units called casting segments. Insulation was applied to the inside of the cases and the propellant was bonded to this insulation.

The semiliquid, solid propellant was poured into casting segments and cured over 4 days. Approximately forty 2.7-metric-ton (3-ton) mixes of propellant were required to fill each segment.

The nozzle consisted of layers of glass- and carbon-cloth materials bonded to aluminum and steel structures. These materials were wound at specified angles and then cured to form a dense, homogeneous insulating material capable of withstanding temperatures reaching 3,300°C (6,000°F). The cured components were then adhesively bonded to their metal support structures and the metal sections were joined to form the complete nozzle assembly.

Transporting a flight set of two Solid Rocket Motors to KSC required four major railroads, nine railcars, and 7 days.

KSC teams refurbished, assembled, tested, and integrated many SRB elements, including the forward and aft skirts, separation motors, frustum, parachutes, and nose cap.

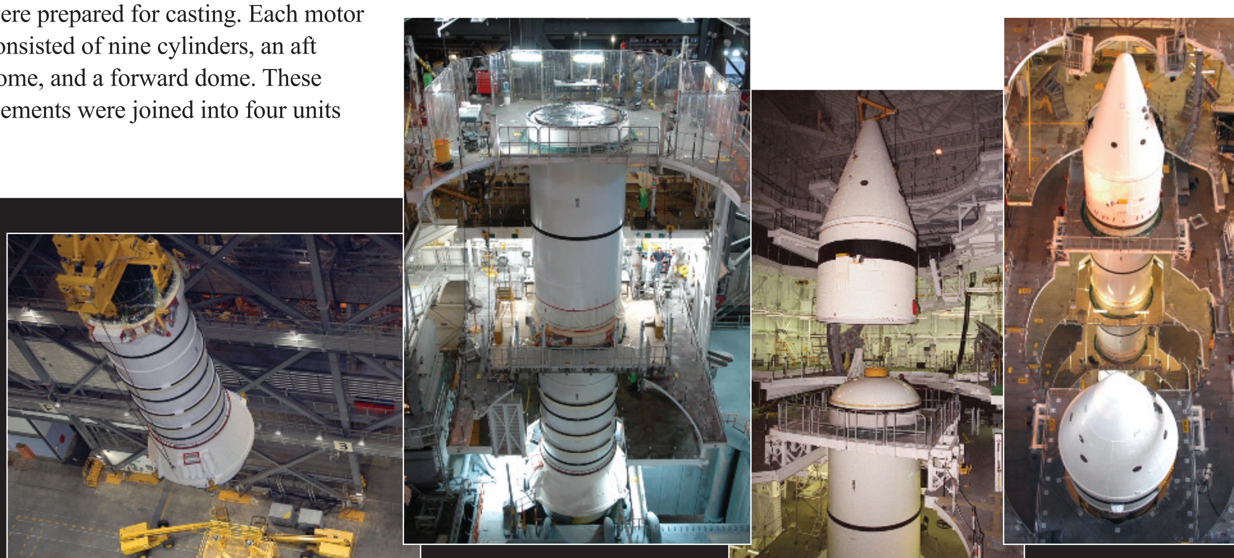
Technicians at the Rotation Processing and Surge Facility received, inspected, and offloaded the booster segments from rail cars, then rotated the segments from horizontal to vertical and placed them on pallets.

Many booster electrical, mechanical, thermal, and pyrotechnic subsystems were integrated into the flight structures. The aft skirt subassembly and forward skirt assembly were processed and then integrated with the booster aft segments.

After a complete flight set of boosters was processed and staged in the surge buildings, the boosters were transferred to the Vehicle Assembly Building for stacking operations.

External Tank Processing

The ET provided propellants to the main engines during launch. The tank was manufactured at the Michoud Assembly Facility in New Orleans and shipped to Port Canaveral in Florida. It was towed by one of NASA’s SRB retrieval ships. At the port, tugboats moved the barge upriver to the KSC turn basin. There, the



Inside the Vehicle Assembly Building, technicians complete the process of stacking the Solid Rocket Booster components.

Vehicle Assembly Building (continued)

tank was offloaded and transported to the Vehicle Assembly Building.

Payload Processing

Payload processing involved a variety of payloads and processing requirements.

The cargo integration test equipment stand simulated and verified payload/cargo mechanical and functional interfaces with the Orbiter before the spacecraft was transported to the launch pad. Payload processing began with power-on health and status checks, functional tests, computer and communications interface checks, and spacecraft command and monitor tests followed by a test to simulate all normal mission functions through payload deployment.

Hubble Space Telescope servicing missions provided other challenges. Sensitive telescope instruments required additional cleaning and hardware handling procedures. Payload-specific ground support equipment had to be installed and monitored throughout the pad flow, including launch countdown.

William Parsons
Space Shuttle program manager (2003-2005) and director of Kennedy Space Center (2007-2008).

In the firing room, William Parsons (left), director of Kennedy Space Center, and Dave King, director of Marshall Space Flight Center, discuss the imminent launch of STS-124 (2008).

"The shuttle is an extremely complex space system. It is surprising how many people and vendors touch the vehicle. At the Kennedy Space Center, it is amazing to me how we are able to move a behemoth space structure, like the Orbiter, and mate to another structure with incredibly precise tolerances."

Following processing, payloads were installed in the Orbiter either horizontally at the Orbiter Processing Facility or vertically at the launch pad.

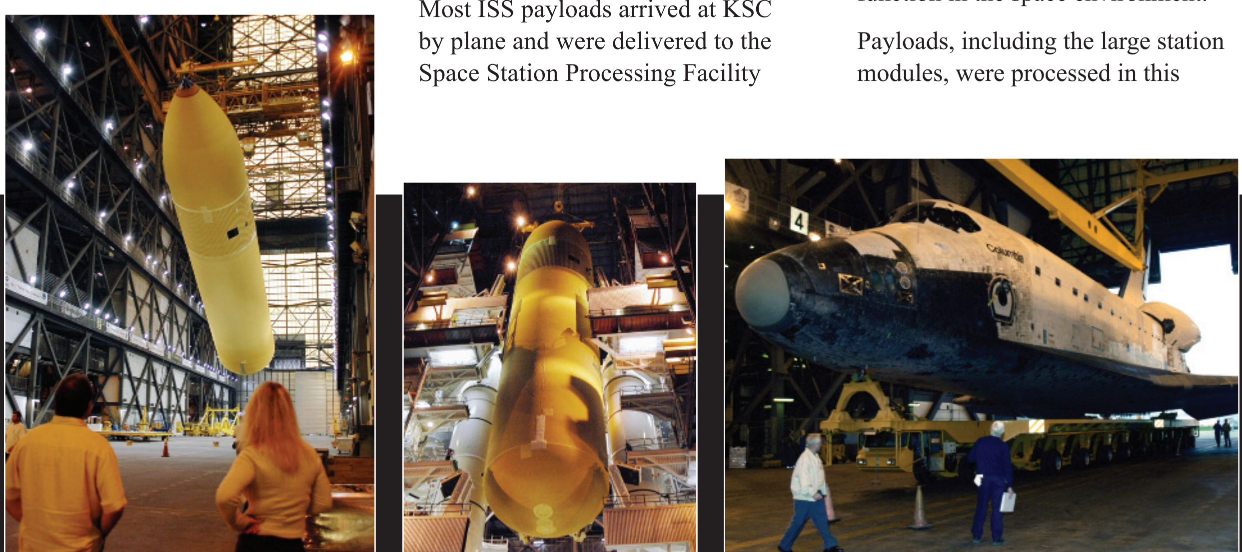
Space Station Processing Facility Checkout

All space station elements were processed, beginning with Node 1 in 1997.

Most ISS payloads arrived at KSC by plane and were delivered to the Space Station Processing Facility where experiments and other payloads were integrated.

ISS flight hardware was processed in a three-story building that had two processing bays, an airlock, operational control rooms, laboratories, logistic areas, and office space. For all payloads, contamination by even the smallest particles could impair their function in the space environment.

Payloads, including the large station modules, were processed in this



After the External Tank is mated to the Solid Rocket Booster, the Orbiter is brought to the Vehicle Assembly Building.

state-of-the-art, nonhazardous facility that had a nonconductive, air-bearing pallet compatible floor. This facility had a Class 100K clean room that regularly operated in the 20K range. Class 100K refers to the classification of a clean room environment in terms of the number of particles allowed. In a Class 100K, 0.03 m^3 (1 ft^3) of air is allowed to have 100,000 particles whose size is 0.5 micrometer (0.0002 in.).

Vehicle Assembly Integration for Launch

The SRB, ET, and Orbiter were vertically integrated in the Vehicle Assembly Building.

Mobile Launch Platform

Technicians inside the building stacked the shuttle on one of three mobile launcher platforms originally built in 1964 for the Apollo moon missions. These platforms were modified to accommodate the weight of the shuttle and still be transportable by crawler transporters, and to handle the increased pressure and heat caused by the SRBs. NASA strengthened the platform deck and added an over-pressurization water deluge system. Two additional flame trenches accommodated the SRB exhaust. Tail service masts, also added, enabled cryogenic fueling and electrical umbilical interfaces.

Technology inside the mobile launcher platforms remained basically unchanged for the first half of the program, reusing much of the Apollo-era hardware. The Hazardous Gas Leak Detection System was the first to be updated. It enabled engineers in the firing room to monitor levels of hydrogen gas in and around the vehicle. Many manual systems also were automated and some could be controlled from remote locations other than the firing rooms.

Assembly

Massive Cranes

The size and weight of shuttle components required a variety of lifting devices to move and assemble the vehicle. Two of the largest and most critical were the 295-metric-ton (325-ton) and 227-metric-ton (250-ton) cranes. The 295-metric-ton (325-ton) cranes lifted and positioned the Solid Rocket Motor sections, ET, and Orbiter. The 227-metric-ton (250-ton) cranes were backups.

Both cranes were capable of fine movements, down to 0.003 cm (0.001 in.), even when lifting fully rated loads. The 295-metric-ton (325-ton) cranes used computer controls and graphics and could be set to release the brakes and "float" the load, holding the load still in midair using motor control alone without overloading any part of the crane or its motors.

The cranes were located 140 m (460 ft) above the Vehicle Assembly Building ground floor. Crane operators relied on radio direction from ground controllers at the lift location.

The cranes used two independent wire ropes to carry the loads. Each crane carried about 1.6 km (1 mile) of wire rope that was reeved from the crane to the load block many times. The wire ropes were manufactured at the same time and from the same lot to ensure rope diameters were identical

The Orbiter is then mated with the External Tank and the Solid Rocket Booster.

Vehicle Assembly Building (continued)

and would wind up evenly on the drum as the load was raised.

Stacking the Orbiter, External Tank, and Solid Rocket Booster

SRB segments were moved to the Vehicle Assembly Building. A lifting beam was connected to the booster clevis using the 295-metric-ton (325-ton) crane hook. The segment was lifted off the pallet and moved into the designated high bay, where it was lowered onto the hold-down post bearings on the mobile launcher platform. Remaining segments were processed and mated to form two complete boosters.

Next in the stacking process was hoisting the ET from a checkout cell, lowering into the integration cell, and mating it to the SRBs. Additional inspections, tests, and component installations were then performed.

The Orbiter was towed from the Orbiter Processing Facility to the Vehicle Assembly Building transfer aisle, raised to a vertical position, lowered onto the mobile launcher platform, and mated. Following inspections, tests, and installations, the integrated shuttle vehicle was ready for rollout to the launch pad.

Rollout to Launch Pad

Technicians retracted the access platforms, opened the Vehicle Assembly Building doors, and moved the tracked crawler transporter vehicle under the mobile launcher platform that held the assembled shuttle vehicle.

The transporter lifted the platform off its pedestals and rollout began. The trip to the launch pad took about 6 to 8 hours along the specially built crawlerway—two lanes of river gravel separated by a median strip. The rock surface supported the weight of the crawler and shuttle, and it reduced vibration. The crawler's maximum unloaded speed was 3.2 km/hr (2 mph) and 1.6 km/hr (1 mph) loaded.

Engineers and technicians on the crawler, assisted by ground crews, operated and monitored systems during rollout while drivers steered the vehicle toward the pad. The crawler leveling system kept the top of the shuttle vertical within +/-10 minutes of 1 degree of arc—the diameter of a basketball. The system also provided the leveling required to negotiate the 5% ramp leading to the launch pads and keep the load level when raised and lowered on pedestals at the pad.

Launch Pad Operations

Once the crawler lowered the mobile launcher platform and shuttle onto a launch pad's hold-down posts, a team began launch preparations. These required an average of 21 processing days to complete.

The two steel towers of Launch Pads 39A and 39B stood 105.7 m (347 ft) above KSC's coastline, atop 13-m- (42-ft)-thick concrete pads. Each complex housed a fixed service structure and a rotating service structure that provided access to electrical, pneumatic, hydraulic, hypergolic, and high-pressure gas lines to support vehicle servicing while protecting the shuttle from inclement weather. Pad facilities also included hypergolic propellant storage (nitrogen tetroxide and monomethylhydrazine),

Once the process is complete, the Space Shuttle is transported to the launch pad.

Crawler moving the shuttle stack to the launch pad.

Launch Pad: 28-30 days

cryogenic propellant storage (liquid hydrogen and liquid oxygen), a water tower, a slide wire crew escape system, and a pad terminal connection room.

Liquid Hydrogen/Liquid Oxygen—Tankers, Spheres

Chicago Bridge & Iron Company built the liquid hydrogen and liquid oxygen storage spheres in the 1960s for the Apollo Program. The tanks were two concentric spheres. The inner stainless-steel sphere was suspended inside the outer carbon-steel sphere using long support rods to allow thermal contraction and minimize heat conduction from the outside environment to the propellant. The space between the two spheres was insulated to keep the extremely cold propellants in a liquid state. For liquid hydrogen, the temperature is -253°C (-423°F); for liquid oxygen, the temperature is -183°C (-297°F).

The spheres were filled to near capacity prior to a launch countdown. A successful launch used about 1.7 million L (450,000 gal) of liquid hydrogen and about 830,000 L (220,000 gal) of liquid oxygen. A launch scrub consumed about

Technicians in the Payload Changeout Room at Launch Pad 39B process the Hubble Space Telescope for STS-31 (1990).

380,000 L (100,000 gal) of each commodity. The spheres contained enough propellant to support three launch attempts before requiring additional liquid from tankers.

Pad Terminal Connection Room

The Pad Terminal Connection Room was a reinforced-concrete room located on the west side of the flame trench, underneath the elevated launch pad hardstand. It was covered with about 6 m (20 ft) of dirt fill and housed the equipment that linked elements of the shuttle, mobile launcher platform, and pad with the Launch Processing System in the Launch Control Center. NASA performed and controlled checkout, countdown, and launch of the shuttle through the Launch Processing System.

Payload Changeout Room

Payloads were transported to the launch pad in a payload canister. At the pad, the canister was lifted with a 81,647-kg (90-ton) hoist and its doors were opened to the Payload Changeout Room—an enclosed, environmentally controlled area mated to the Orbiter payload bay. The payload ground-handling mechanism—a rail-suspended, mechanical structure measuring 20 m (65 ft) tall—captured the payload with retention fittings that used a water-based hydraulic system with gas-charged accumulators as a cushion. The mechanism, with the payload, was then moved to the aft wall of the Payload Changeout Room, the main doors were closed, and the canister

The Space Shuttle arrives at the launch pad, where payloads are installed into the Orbiter cargo bay.

Payload Changeout Room at launch pad.

was lowered and removed from the pad by the transporter.

Once the rotating service structure was in the mate position and the Orbiter was ready with payload bay doors open, technicians moved the payload ground-handling mechanism forward and installed the payload into the Orbiter cargo bay. This task could take as many as 12 hours if all went well. When installation was complete, the payload was electrically connected to the Orbiter and tested, final preflight preparations were made, and the Orbiter payload bay doors were closed for flight.

Sound Suppression

Launch pads and mobile launcher platforms were designed with a water deluge system that delivered high-volume water flows into key areas to protect the Orbiter and its payloads from damage by acoustic energy and rocket exhaust.

The water, released just prior to main engine ignition, flowed through pipes measuring 2.1 m (7 ft) in diameter for about 20 seconds. The mobile launcher platform deck water spray system was fed from six 3.7-m- (12-ft)-high water spray diffusers nozzles dubbed “rainbirds.”

Water spray at the launch pad was used to suppress the acoustic vibration during launch.

Operational Systems—Test and Countdown

Launch Processing System

Engineers used the Launch Processing System computers to monitor thousands of shuttle measurements and control systems from a remote and safe location. Transducers, built into on-board systems and ground support equipment, measured each important function (i.e., temperature, pressure). Those measurements were converted into engineering data and delivered to the Launch Processing System in the firing rooms, where computer displays gave system engineers detailed views of their systems.

The unique Launch Processing System software was specifically written to process measurements and send commands to on-board computers and ground support equipment to control the various systems. The software reacted either to measurements reaching predefined values or when the countdown clock reached a defined time.

Launch was done by the software. If there were no problems, the button to initiate that software was pushed at the designated period called T minus 9 minutes (T=time). One of the last commands sent to the vehicle was “Go for main engine start,” which was sent 10 seconds before launch. From that point on, the on-board computers were in control. They ignited the main engines and the SRBs.

In the firing room at Kennedy Space Center, NASA clears the Space Shuttle for launch.

STS-108 (2001) launch.

Training and Simulations

Launch Countdown Simulation

The complexity of the shuttle required new approaches to launch team training. During Mercury, Gemini, and Apollo, a launch-day rehearsal involving the launch vehicle, flight crew, and launch control was adequate to prepare for launch. The shuttle, however, required more than just one rehearsal.

Due to processing and facility requirements, access to actual hardware in a launch configuration only occurred near the actual launch day after the vehicle was assembled and rolled to the launch pad. The solution was to write a computer program that simulated shuttle telemetry data with a computer math model and fed those data into launch control in place of the actual data sent by a shuttle on the pad.

Terminal Countdown Demonstration Test

The Terminal Countdown Demonstration Test was a dress rehearsal of the terminal portion of the launch countdown that included the flight crew suit-up and flight crew loading into the crew cabin. The Orbiter was configured to simulate a launch-day posture, giving the flight crew the opportunity to run through all required procedures. The flight crew members also was trained in emergency egress from the launch pad, including use of emergency equipment, facility fire-suppression systems, egress routes, slidewire egress baskets, emergency bunker, emergency vehicles, and the systems available if they needed to egress the launch pad.

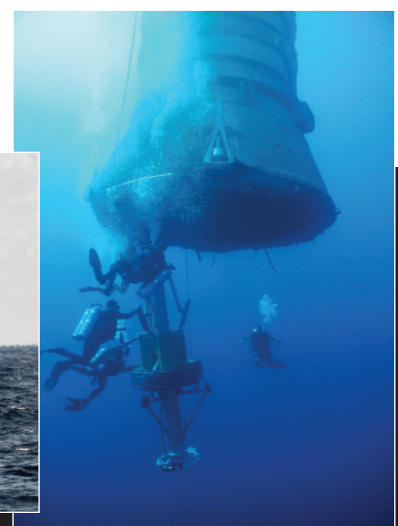
Space Station Processing Facility for modules and other hardware at Kennedy Space Center.

Special Facilities and Tools

Facility Infrastructure

Although the types of ground systems at KSC were common in many large-scale industrial complexes, KSC systems often were unique in their application, scale, and complexity.

The Kennedy Complex Control System was a custom-built commercial facility control system that included



After launch, Solid Rocket Boosters separate from the Space Shuttle and are recovered in the Atlantic Ocean, close to Florida's East Coast.

Solid Rocket Booster Recovery

about 15,000 monitored parameters, 800 programs, and 300 different displays. In 1999, it was replaced with commercial off-the-shelf products.

The facility heating, ventilating, and air conditioning systems for Launch Pads 39A and 39B used commercial systems in unique ways. During launch operations that required hazard proofing of the mobile launcher platform, a fully redundant fan—149,140 W (200 hp), 1.12 m (44 in.) in diameter—pressurized the mobile launcher platform and used more than 305 m (1,000 ft) of 1.2- by 1.9-m (48- by 75-in.) concrete sewer pipe as ductwork to deliver this pressurization air.

Facility systems at the Orbiter Processing Facility high bays used two fully redundant, spark-resistant air handling units to maintain a Class 100K clean work area in the 73,624-m^3 (2.6-million-ft^3) high bay. During hazardous operations, two spark-resistant exhaust fans, capable of exhausting 2,492 m^3/min (88,000 ft^3/min), worked in conjunction with high bay air handling units and could replace the entire high bay air volume in fewer than 30 minutes.

The launch processing environment included odorless and invisible gaseous commodities that could pose safety threats. KSC used an oxygen-deficiency monitoring system to continuously monitor confined-space oxygen content. If oxygen content fell below 19.5%, an alarm was sounded and beacons flashed, warning personnel to vacate the area.

Communications and Tracking

Shuttle communications systems and equipment were critical to safe vehicle operation. The communications and tracking station in the Orbiter Processing Facility provided test, checkout, and troubleshooting for Orbiter preflight, launch, and landing activities. Communications and tracking supported Orbiter communications and navigations subsystems.

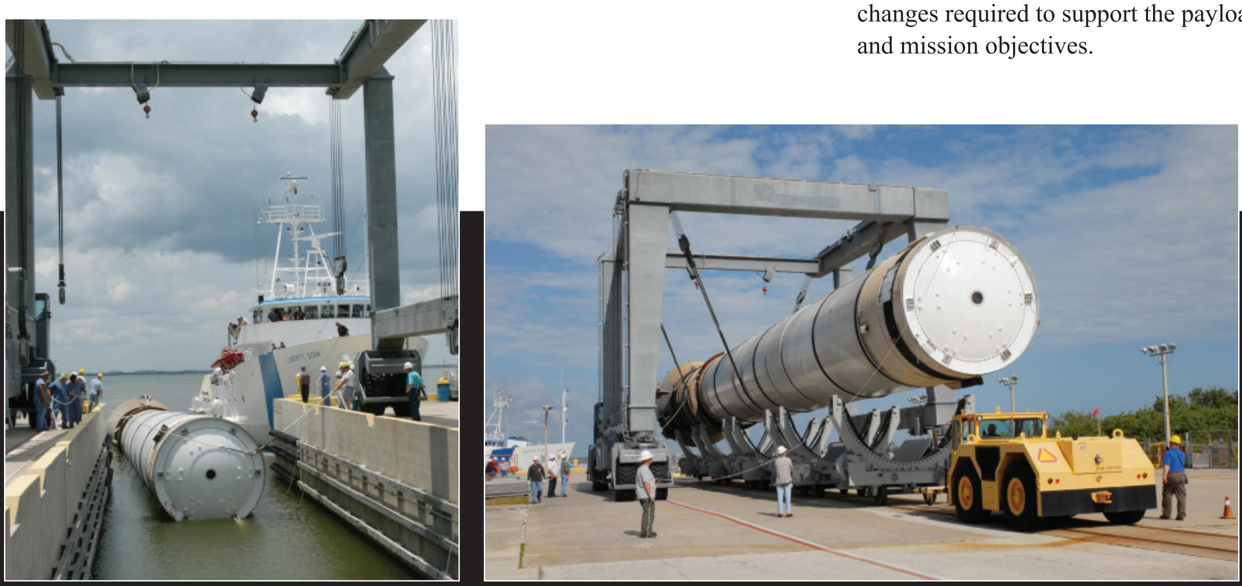
Following landing at KSC, the communications and tracking station monitored the Orbiter and Merritt Island Launch Area communications transmissions during tow and spotting of the vehicle in the Orbiter Processing Facility. In that facility, the station was configured as a passive repeater to route the uplink and downlink radio frequency signals to and from the Orbiter Processing Facility and Merritt Island Launch Area using rooftop antennas.

Operations Planning Tools

Requirements and Configuration Management

Certification of Flight Readiness was the process by which the Space Shuttle Program manager determined the shuttle was ready to fly. This process verified that all design requirements were properly approved, implemented, and closed per the established requirements and configuration management processes in place at KSC.

Requirements and configuration management involved test requirements and modifications. Test requirements ensured shuttle integrity, safety, and performance. Modifications addressed permanent hardware or software changes, which improved the safety of flight or vehicle performance, and mission-specific hardware or software changes required to support the payload and mission objectives.



The recovered Solid Rocket Boosters are returned to Kennedy Space Center for refurbishment and reusability.

NASA generated planning, executing, and tracking products to ensure the completion of all processing flow steps. These included: process and support plans; summary and detailed assessments; milestone, site, maintenance, and mini schedules; and work authorization documents. Over time, many operations tools evolved from pen and paper, to mainframe computer, to desktop PC, and to Web-based applications.

Work authorization documents implemented each of the thousands of requirements in a flow. Documents included standard procedures performed every flow as well as nonstandard documents such as problem and discrepancy reports, test preparation sheets, and work orders.

Kennedy Space Center Integrated Control Schedule

The KSC Integrated Control Schedule was the official, controlling schedule for all work at KSC's shuttle processing sites. This integration tool reconciled conflicts between sites and resources among more than a dozen independent sites and multiple shuttle missions in work simultaneously. Work authorization documents could not be performed unless they were entered on this schedule, which distributed the required work authorization documents over time and sequenced the work in the proper order over the duration of the processing flow. The schedule, published on the Web every workday, contained the work schedule for the following 11 days for each of the 14 shuttle processing sites, including the three Orbiter Processing Facility bays, Vehicle Assembly Building, launch pads, Shuttle Landing Facility, and Hypergolic Maintenance Facility.

Space Shuttle Launch Countdown Operations

Launch countdown operations occurred over a period of about 70 hours during which NASA activated, checked out, and configured the shuttle vehicle systems to support launch. Initial operations configured shuttle data and computer systems. Power Reactant Storage and Distribution System loading was the next major milestone in the countdown operation. Liquid oxygen and liquid hydrogen had to be transferred from tanker trucks on the launch pad surface, up the fixed service structure, across the rotating service structure, and into the on-board storage tanks, thus providing the oxygen and hydrogen gas that the shuttle fuel cells required to supply power and water while on orbit.

The next major milestones were activation of the communication equipment and movement of the rotating service structure from the mate position (next to the shuttle) to the park position (away from the shuttle), which removed much access to the vehicle.

The most hazardous operation, short of launch, was loading the ET with liquid oxygen and liquid hydrogen. This was performed remotely from the Launch Control Center. The Main Propulsion System had to be able to control the flow of cryogenic propellant through a wide range of flow rates. The liquid hydrogen flow through the vehicle was as high as 32,550 L/min (8,600 gal/min). While in stable replenish, flow rates as low as 340 L/min (90 gal/min) had to be maintained with no adverse affects on the quality of the super-cold propellant.

Once the tank was loaded and stable, NASA sent teams to the launch pad. One team inspected the vehicle for issues that would prevent launch, including ice formation and cracks in the ET foam associated with the tank loading. Another team configured the crew cabin and the room used to access the shuttle cabin. Flight crew members, who arrived a short time later, were strapped into their seats and the hatch was secured for launch.

The remaining operations configured the vehicle systems to support the terminal countdown. At that point, the ground launch sequencer sent the commands to perform the remaining operations up to 31 seconds before launch, when the on-board computers took over the countdown and performed the main engine start and booster ignition.

Solid Rocket Booster Recovery

Following shuttle launch, preparations continued for the next mission, beginning with SRB recovery.

Approximately 1 day before launch, the two booster recovery ships—Freedom Star and Liberty Star—left Cape Canaveral Air Force Station and

Port Canaveral to be on station prior to launch to retrieve the boosters from the Atlantic Ocean.

Approximately 6½ minutes after launch, the boosters splashed down 258 km (160 miles) downrange. Divers separated the three main parachutes from each booster and the parachutes were spun onto reels on the decks of each ship. The divers also retrieved drogue chutes and frustums and lifted them aboard the ships.

For the boosters to be towed back to KSC, they were repositioned from vertical to horizontal. Divers placed an enhanced diver-operated plug into the nozzle of the booster, which was 32 m (105 ft) below the ocean surface. Air was pumped into the boosters, displacing the water inside them and repositioning the boosters to horizontal. The boosters were then moved alongside the ships for transit to Cape Canaveral Air Force Station where they were disassembled and refurbished. Nozzles and motor segments were shipped to the manufacturer for further processing.

Following recovery, the segments were taken apart and the joints were inspected to make sure they had performed as expected. Booster components were inspected and hydrolased—the ultimate pressure cleaning—to remove any residual fuel and other contaminants. Hydrolasing was done manually with a gun operating at 103,421 kPa (15,000 psi) and robotically at up to 120,658 kPa (17,500 psi). Following cleaning, the frustum and forward skirt were media-blasted and repainted.

Parachutes

SRB main parachute canopies were the only parachutes in their size class that were refurbished. NASA removed the parachutes from the retrieval ships and transported them to the Parachute Refurbishment Facility.

At the facility, technicians unspooled, defouled, and inspected the parachutes. Following a preliminary damage mapping to assess the scope of repairs required, the parachutes were hung on a monorail system that facilitated movement through the facility. The first stop was a 94,635-L (25,000-gal) horizontal wash tank where each parachute underwent a 4- to 6-hour fresh water wash cycle to remove all foreign material. The parachutes were transferred to the drying room and exposed to 60°C (140°F) air for 10 to 12 hours, after which they were inspected, repaired, and packed into a three-part main parachute cluster and transferred to the Assembly and Refurbishment Facility for integration into a new forward assembly.

Summary

In conclusion, the success of each shuttle mission depended, without exception, on ground processing. The series of planning and execution steps required to process the largest and most complex reusable space vehicle was representative of NASA's ingenuity, dedicated workforce, and unmatched ability, thus contributing immensely to the legacy of the Space Shuttle Program.

Technicians assemble a Solid Rocket Booster parachute at Kennedy Space Center.

Space Operations Weather: How NASA, the National Weather Service, and the Air Force Improved Predictions

Weather was the largest single cause of delays or scrubs of launch, landing, and ground operations for the Space Shuttle.

Rollout of Space Shuttle Discovery, STS-128 (2009), was delayed by onset of lightning in the area of Launch Pad 39A at Kennedy Space Center. Photo courtesy of Environmental Protection Agency.

The Shuttle Weather Legacy

NASA and the US Air Force (USAF) worked together throughout the program to find and implement solutions to weather-related concerns. The Kennedy Space Center (KSC) Weather Office played a key role in shuttle weather operations. The National Weather Service operated the Spaceflight Meteorology Group at Johnson Space Center (JSC) to support on-orbit and landing operations for its direct customers—the shuttle flight directors. At Marshall Space Flight Center, the Natural Environments Branch provided expertise in climatology and analysis of meteorological data for both launch and landing operations with emphasis on support for engineering analysis and design. The USAF 45th Weather Squadron provided the operational weather observations and forecasting for ground operations and launch at the space launch complex. This collaborative community, which worked effectively as a team across the USAF, NASA, and the National Weather Service, not only improved weather prediction to support the Space Shuttle Program and spaceflight worldwide in general, it also contributed much to our understanding of the atmosphere and how to observe and predict it. Their efforts not only enabled safe ground launch and landing, they contributed to atmospheric science related to observation and prediction of lightning, wind, ground and atmosphere, and clouds.

By the late 1980s, 50% of all launch scrubs were caused by adverse weather conditions—especially the destructive effects of lightning, winds, hail, and temperature extremes. So NASA and their partners developed new methods to improve the forecasting of weather phenomena that threatened missions, including the development of technologies for lightning, winds, and other weather phenomena. The Space Shuttle Program led developments and innovations that addressed weather conditions specific to Florida, and largely supported and enhanced launch capability from the Eastern Range. Sensor technologies developed were used by, and shared with, other meteorological organizations throughout the country.

Living With Lightning, a Major Problem at Launch Complexes Worldwide

Naturally occurring lightning activity associated with thunderstorms occurs at all launch complexes, including KSC and Cape Canaveral Air Force Station. Also, the launch itself can trigger lightning—a problem for launch complexes that have relatively infrequent lightning may have a substantial potential for rocket-triggered lightning. The launch complex at Vandenberg Air Force Base, California, is a primary example.

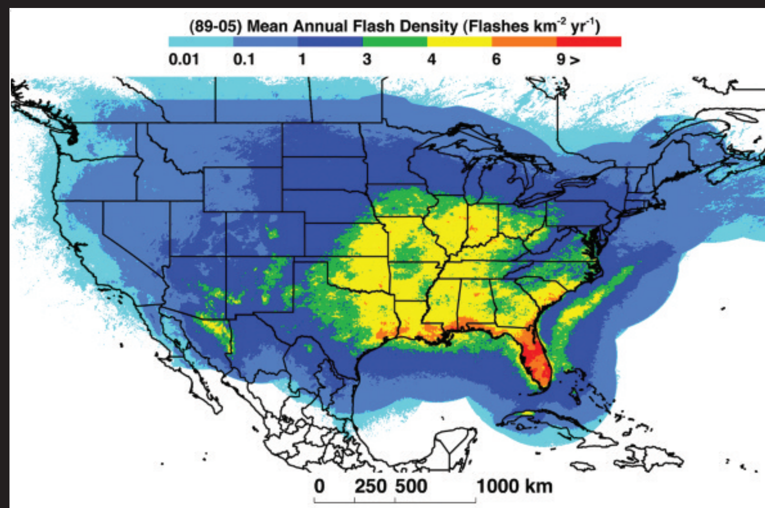
Natural lightning discharges may occur within a single thundercloud, between thunderclouds, or as cloud-to-ground strikes. Lightning may also be triggered by a conductive object, such as a Space Shuttle, flying into a region of atmosphere where strong electrical charge exists but is not strong enough by itself to discharge as a lightning strike.

Natural lightning is hazardous to all aerospace operations, particularly those that take place outdoors and away from protective structures. Triggered lightning is only a danger to vehicles in flight but, as previously described, may occur even when natural lightning is not present.

Lightning Technology at the Space Launch Complex

Crucial to the success of shuttle operations were the activities of the USAF 45th Weather Squadron, which provided all launch and landing orbit weather support for the space launch complex. Shuttle landing support was provided by the National Weather Service Spaceflight Meteorology Group located at JSC. The 45th Weather Squadron operated from Range Weather Operations at Cape Canaveral Air Force Station. The Spaceflight Meteorology Group housed weather system computers for forecast and also analyzed data from the National Centers for Environmental Prediction, weather satellite imagery, and local weather sensors as well as assisted in putting together KSC area weather forecasts.

Lightning Flash Density at Launch Complexes



Flash density is a measure of how many lightning flashes occur in a particular area or location over time. Florida, and particularly the space launch complex, receives the highest density of lightning flashes in the contiguous 48 states. Review of lightning flash activity at the complex over many years shows that the highest average activity levels occur between June and September, and the lowest levels between November and January.

Another key component of shuttle operations was the KSC Weather Office, established in the late 1980s. The KSC Weather Office ensured all engineering studies, design proposals, anomaly analyses, and ground processing and launch commit criteria for the shuttle were properly considered. It coordinated all weather research and development, incorporating results into operations.

Lightning Evaluation Tools	System Network
Launch Pad Lightning Warning System	Thirty-one electric-field mills that serve as an early warning system for electrical charges building aloft due to a storm system.
Lightning Detection and Ranging	Nine antennas that detect and locate lightning in three dimensions within 185 km (100 nautical miles) using a "time of arrival" computation on signals.
National Lightning Detection Network	One-hundred ground-based sensing stations that detect cloud-to-ground lightning activity across the continental US. The sensors instantaneously detect the electromagnetic signal given off when lightning strikes the ground.
Cloud-to-Ground Lightning Surveillance System	Six sensors spaced much closer than in the National Lightning Detection Network.
Weather Radar	Two radars that provide rain intensity and cloud top information.

Systems used for weather and thunderstorm prediction and conditions.

Launch Pad Lightning Warning System data helped forecasters determine when surface electric fields may have been of sufficient magnitude to create triggered lightning during launch. The data also helped determine when to issue and cancel lightning advisories and warnings. The original Lightning Detection and Ranging System, developed by NASA at KSC, sensed electric fields produced by the processes of breakdown and channel formation in both cloud lightning and cloud-to-ground flashes. The locational accuracy of this system was on the order of +/-100 m (328 ft). In 2008, a USAF-owned system replaced the original KSC Lightning Detection and Ranging System, which served the space launch complex for about 20 years.

The National Lightning Detection Network plots cloud-to-ground lightning nationwide and was used to identify cloud-to-ground strikes at KSC and to ensure safe transit of the Orbiter atop the Shuttle Carrier Aircraft. A National Lightning Detection Network upgrade in 2002-2003 enabled the system to provide a lightning flash-detection efficiency of approximately 93% of all flashes with a location accuracy on the order of +/-500 to 600 m (1,640 to 1,968 ft).

The Cloud-to-Ground Lightning Surveillance System is a lightning detection system designed to record cloud-to-ground lightning strikes in the vicinity of the space launch complex. A Cape Canaveral Air Force Station upgrade in 1998 enabled the system to provide a lightning flash-detection efficiency within the sensor array of approximately 98% of all flashes and with a location accuracy on the order of +/-250m (820 ft).

The Lightning Detection and Ranging System was completely upgraded during the shuttle era with new sensors positioned in nine locations around the space launch complex proper. Along with a central processor, the system was referred to as the Four-Dimensional Lightning Surveillance System. This new central processor was also capable of processing the Cloud-to-Ground Lightning Surveillance System sensor data at the same time and, moreover, produced full cloud-to-ground stroke data rather than just the first stroke in real time. The synergistic combination of the upgraded Four-Dimensional Lightning Surveillance System and the Cloud-to-Ground Lightning Surveillance System provided a more accurate and timely reporting capability over that of the upgraded Cloud-to-Ground Lightning Surveillance System or the older Lightning Detection and Ranging System individually, and it allowed for enhanced space launch operations support.

Launch and landing forecasters located in Texas, and Cape Canaveral, Florida, accessed displays from two different Florida radar sites—one located at Patrick Air Force Base, and a NEXRAD (next-generation weather radar) Doppler, located in Melbourne at the National Weather Service.

Lightning Operational Impacts; Warning Systems

The likelihood of sustaining damage from natural lightning was reduced by minimizing exposure of personnel and hardware during times when lightning threatened. To accomplish this, it was necessary to have in place a balanced warning system whereby lightning activity could be detected and reported far enough in advance to permit protective action to be taken. Warnings needed to be accurate to prevent harm yet not stop work unnecessarily. Lightning advisories were important for ground personnel, launch systems, and the transport of hardware, including the 6- to 8-hour transport of the Space Shuttle to the launch pad.

The original deployment of the Lightning Detection and Ranging System pioneered a two-phase lightning policy. In Phase I, an advisory was issued that lightning was forecast within 8 km (5 miles) of the designated site within 30 minutes of the effective time of the advisory. The 30-minute warning gave personnel time to get to a protective shelter and gave personnel working on lightning-sensitive tasks time to secure operations in a safe and orderly manner. A Phase II warning was issued when lightning was imminent or occurring within 8 km (5 miles) of the designated site. All lightning-sensitive operations were terminated until the Phase II warning was lifted. This two-phase policy provided adequate lead time for sensitive operations without shutting down less-sensitive operations until the hazard became immediate. Much of this activity was on the launch pads, which were tall, isolated, narrow structures in wide-open areas and were prime targets for lightning strikes. Lightning advisories were critical for the safety of over 25,000 people and resource protection of over $18 billion in facilities. Several more billion dollars could be added to this value, depending on what payloads and rockets were at the launch pads or in transit outside. This policy ultimately reduced ground processing downtime by as much as 50% compared to the older system, saving millions of dollars annually.

Operationally, warnings were sometimes not sufficient, for example during launch operations when real-time decisions had to be made based on varying weather conditions with a potentially adverse effect on flight. Following a catastrophic lightning-induced failure of an Atlas/Centaur rocket in 1987, a blue-ribbon "Lightning Advisory Panel" comprising top American lightning scientists was convened to assist the space program. The panel recommended a set of "lightning launch commit criteria" to avoid launching into an environment conducive to either natural or triggered lightning. These criteria were adopted by NASA for the Space Shuttle Program, and also by the USAF for all military and civilian crewless launches from the Eastern and Western Ranges.

Hail Damage to the External Tank

ET-124 damage repairs, post storm.

On the afternoon of February 26, 2007, during STS-117 prelaunch processing at Kennedy Space Center (KSC) Launch Pad A, a freak winter thunderstorm with hail struck the launch complex and severely damaged the External Tank (ET) (ET-124) Thermal Protection System foam insulation. The hail strikes caused approximately 7,000 divots in the foam material. The resulting damage revealed that the vehicle stack would have to be returned to the Vehicle Assembly Building to access the damage. This would be the second time hail caused the shuttle to be returned to the building. To assess the damage, NASA built customized scaffolding. The design and installation of the scaffolding needed to reach the sloping forward section of the tank was a monumental task requiring teams of specialized riggers called "High Crew" to work 24 hours a day for 5 straight days. A hand-picked engineering assessment team evaluated the damage. The ET liquid oxygen tank forward section was the most severely damaged area and required an unprecedented repair effort. There were thousands of damaged areas that violated the ET engineering acceptance criteria for flight. NASA assembled a select repair team of expert technicians, quality inspectors, and engineers to repair the damage. This team was assisted by manufacturing specialists from Lockheed Martin, the ET manufacturer, and Marshall Space Flight Center.

KSC developed an inexpensive, unique hail monitoring system using a piezoelectric device and sounding board to characterize rain and hail. While the shuttle was at the pad, three remote devices constantly monitored the storms for potential damage to the vehicle.

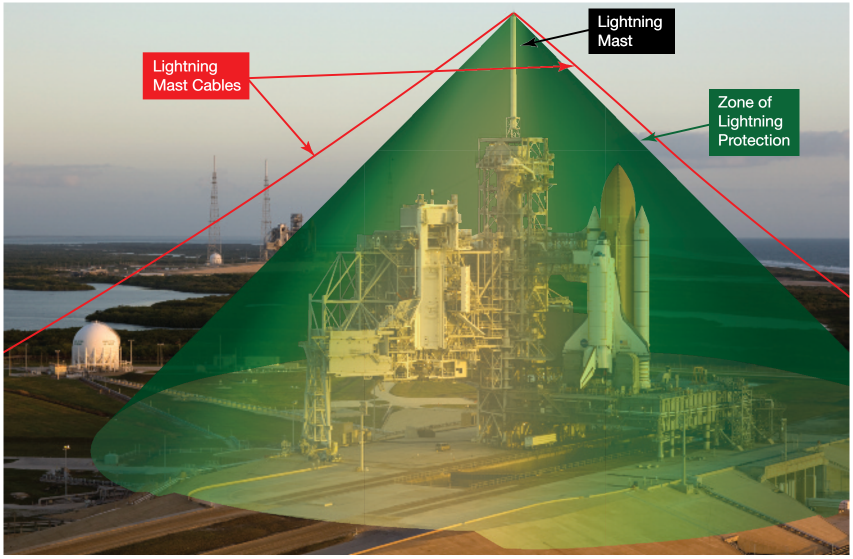
The lightning launch commit criteria, as initially drafted, were very conservative as electrical properties of clouds were not well understood. Unfortunately, this increased the number of launches that had to be postponed or scrubbed due to weather conditions. The program undertook a series of field research initiatives to learn more about cloud electrification in hopes that the criteria could safely be made less restrictive.

These field research initiatives used aircraft instrumented with devices called electric field mills that could measure the strength of the electric field in clouds as the aircraft flew through them. The research program was known as Airborne Field Mill. Data collected by the Airborne Field Mill program were subjected to extensive quality control, time-synchronized, and consolidated into a carefully documented, publicly accessible online archive. This data set is the largest, most comprehensive of its kind.

The Airborne Field Mill science team developed a quantity called Volume Averaged Height Integrated Radar Reflectivity that could be observed with weather radar. This quantity, when small enough, assured safe electric fields aloft. As a result, the Lightning Advisory Panel was able to recommend changes to the lightning launch commit criteria to make them both safer and less restrictive. The new criteria are used by all US Government launch facilities, and the Federal Aviation Administration is including them in its regulations governing the licensing of private spaceports. These criteria were expressed in detailed rules that described weather conditions likely to produce or be associated with lightning activity, the existence of which precluded launch.

Lightning Protection and Instrumentation Systems

Physical lightning protection for the shuttle on the pad was provided by a combination of a large, loose network of wiring known as a counterpoise beneath the pad structure and surrounding environs and a large wire system comprising a 2.5-cm- (1-in.)-, 610-m- (2,000-ft)-long steel cable anchored and grounded at either end and supported in the middle by a 24.4-m- (80-ft)-tall nonconductive mast. The mast also served to prevent currents—from lightning strikes to the wire—from passing into the pad structure. A 1.2-m (4-ft) air terminal, or lightning rod, was mounted atop the mast and electrically connected to the steel cable. The cable arrangement assumed a characteristic curved shape to either side of the pad described mathematically as a catenary and therefore called the Catenary Wire System.



A grounded stainless-steel cable extends from the lightning mast to provide a zone of protection for the launch vehicle.

Additional lightning protection devices at the launch pads included a grounded overhead shield cable that protected the crew emergency egress slide wires attached to the fixed service structure. Grounding points on the pad surface and the mobile launcher platform and electrical connections in contact with the shuttle completed the system that conducted any lightning-related currents safely away from the vehicle. Overhead grid-wire systems protected hypergolic fuel and oxidizer storage areas. The huge 3,407,000-L (900,000-gal) liquid hydrogen and liquid oxygen tanks at each pad were constructed of metal and did not need overhead protection.

The shuttle and its elements were well protected from both inclement weather and lightning away from the pad while in the Vehicle Assembly Building. This 160-m- (525-ft)-high structure had eleven 8-m- (25-ft)-high lightning conductor towers on its roof. When lightning hit the building's air terminal system, wires conducted the charge to the towers, which directed the current down the Vehicle Assembly Building's sides and into bedrock through the building's foundation pilings.

In addition to physical protection features, the Space Shuttle Program employed lightning monitoring systems to determine the effects of lightning strikes to the catenary system, the immediate vicinity of the launch pad, and the shuttle itself. The shuttle used two specific lightning monitoring systems—the Catenary Wire Lightning Instrumentation System and the Lightning Induced Voltage Instrumentation System. The Catenary Wire Lightning Instrumentation System used sensors located at either end of the Catenary Wire System to sense currents in the catenary wire induced by nearby or direct lightning strikes. The data were then used to evaluate the potential for damage to sensitive electrical equipment on the shuttle. The Lightning Induced Voltage Instrumentation System used voltage taps and current sensors located in the shuttle and the mobile launcher platform to detect and record voltage or current transients in the shuttle Electrical Power System.

After STS-115, NASA performed a system review and decided to upgrade the two systems. The Ground Lightning Monitoring System was implemented. It was comprised of both voltage monitoring on the Orbiter power busses and magnetic field sensing internal to the Orbiter middeck, the aft avionics bay, the Payload Changeout Room, and locations on the pad structure. The collected voltage and magnetic field data were used to determine induced current and voltage threats to equipment, allowing direct comparison to known, acceptable maximum levels for the vehicle and its equipment.

The elaborate lightning detection and personnel protection systems at KSC proved their worth the hard way. The lightning masts at Launch Pads 39A and 39B were struck many times with a shuttle on the pad, with no damage to equipment. No shuttle was endangered during launch, although several launches were delayed due to reported weather conditions.

Ultimately, one of the biggest contributions to aerospace vehicle design for lightning protection was the original standard developed by NASA for the shuttle. New standards developed by the Department of Defense, the Federal Aviation Administration, and

Lightning Delays Launch

In August 2006, while STS-115 was on the pad, the lightning mast suffered a 50,000-ampere attachment, much stronger than the more typical 20,000- to 30,000-ampere events, resulting in a 3-day launch delay while engineers and managers worked feverishly to determine the safety of flight condition of the vehicle. The vehicle, following extensive data review and analysis, was declared safe to fly.

commercial organizations over the years have leveraged this pioneering effort, and the latest of these standards is now applicable for design of the new spacecraft.

Working With Winds

Between the Earth's surface and about 18 km (10 nautical miles) altitude, the Earth's atmosphere is dense enough that winds can have a big effect on an ascending spacecraft. Not only can the wind blow a vehicle toward an undesirable direction, the force of the wind can cause stress on the vehicle. The steering commands in the vehicle's guidance computer were based on winds measured well before launch time. If large wind changes occurred between the time the steering commands were calculated and launch time, it was difficult for the vehicle to fly the desired trajectory or the vehicle would be stressed beyond its limits and break up. Therefore, frequent measurements of wind speed and direction as a function of height were made during countdown.

The Space Shuttle Program measured upper air winds in two ways: high-resolution weather balloons and a Doppler radar wind profiler. Both had a wind speed accuracy of about 1 m/sec (3.3 ft/sec). Balloons had the advantage of being able to detect atmospheric features as small as 100 m (328 ft) in vertical extent, and have been used since the beginning of the space program. Their primary disadvantages were that they took about 1 hour to make a complete profile from the surface to 18 km (11 miles), and they blew downwind. In the winter at KSC, jet stream winds could blow a balloon as much as 100 km (62 miles) away from the launch site before the balloon reached the top of its trajectory.

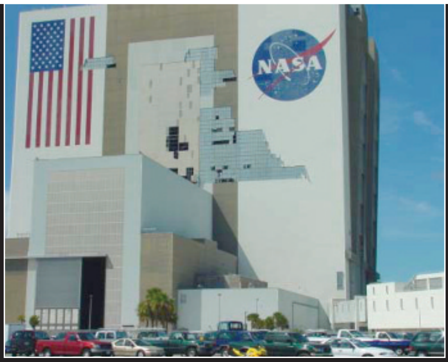
The wind profiler was located near the Shuttle Landing Facility, close to the launch pad. The profiler scattered radar waves off turbulence in the atmosphere and measured their speed in a manner similar to a traffic policeman's radar gun. It produced a complete profile of wind speed and direction every 5 minutes. This produced profiles 12 times faster than a balloon and much closer to the flight path of the vehicle. Its only technical disadvantage was that the smallest feature in the atmosphere it could distinguish was 300 m (984 ft) in vertical extent. The Doppler radar wind profiler was first installed in the late 1980s.

When originally delivered, the profiler was equipped with commercial software that provided profiles with unknown accuracy every 30 minutes. For launch support, NASA desired a higher rate of measurement and accuracy as good as the high-resolution balloons. Although the Median Filter First Guess software, used in a laboratory to evaluate the potential value of the Doppler radar wind profiler, significantly outperformed any commercially available signal processing methodology for wind profilers, it was sufficiently complex and its run time too long for operational use to be practical.

To use wind profiler data, NASA developed algorithms for wind profiles that included the ground wind profile, high-altitude weather balloons, and Doppler radar. This greatly enhanced the safety of space launches.

Hurricane Damage

Space Shuttle processing during Florida's hurricane season was a constant challenge to ground processing. Hurricane weather patterns were constantly monitored by the team. If the storms could potentially cause damage to the vehicle, the stack was rolled back to the Vehicle Assembly Building for protection. During Hurricane Frances in September 2004, Kennedy Space Center suffered major damage resulting from the storm. The Vehicle Assembly Building lost approximately 820 aluminum side panels and experienced serious roof damage.



Damage to Vehicle Assembly Building at Kennedy Space Center during Hurricane Frances.

Landing Weather Forecasts

The most important shuttle landing step occurred just prior to the deorbit burn decision. The National Weather Service Spaceflight Meteorology Group's weather prediction was provided to the JSC flight director about 90 minutes prior to the scheduled landing. This forecast supported the Mission Control Center's "go" or "no-go" deorbit burn decision. The deorbit burn occurred about 60 minutes prior to landing. The shuttle had to land at the specified landing site. The final 90-minute landing forecast had to be precise, accurate, and clearly communicated for NASA to make a safe landing decision.